Microwave absorption in YBa[2]Cu[3]O[7-delta]-manganite superlattices

Piotr Gierlowski, Krzysztof Werner-Malento, Piotr Przyslupski, Cornelis Jacominus van Der Beek

Microwave absorption in $YBa_2Cu_3O_{7-\delta}$-manganite superlattices

P. Gierłowski,* K. Werner-Malento, and P. Przysłupski
Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warszawa, Poland

C. J. van der Beek
Ecole Polytechnique, CNRS-UMR 7642 and CEA/DSM/~~DRECAM~~, 91128 Palaiseau, France

We report on results of direct microwave absorption measurements of $Re_{1-x}B_xMnO_3/YBa_2Cu_3O_{7-\delta}$ half metal/*d*-wave superconductor superlattices (where Re - La and Pr) and (B - Sr and Ca) for microwave frequencies in the range from 9 to 20 GHz. The measurements of the entire heterostructure were performed mostly at temperatures below the superconducting transition. The obtained results strongly depend on the microwave frequency and can be qualitatively described within the theoretical model of high-frequency properties of Josephson junctions with a ferromagnetic barrier proposed by S. Takahashi, S. Hikino, M. Mori, J. Martinek, and S. Maekawa, Phys. Rev. Lett. **99**, 057003 (2007).

Although non-resonant microwave absorption in both ferromagnetic manganite (F) [1, 2] and superconducting high-T_c (S) films [3] has been studied and described extensively in the past, little is known about the microwave absorption in multi-layered superconductor-ferromagnet $[S/F]_n$ structures. These exhibit unique properties, such as the negative refraction index discovered recently at high magnetic fields for millimeter waves [4]. While some experimental low-frequency data have been obtained on simple structures like S/F bilayers and F/S/F trilayers [5], the high-frequency properties of $[S/F]_n$ superlattices have been investigated by ellipsometry only in the far-infrared and sub-mm spectral ranges [6, 7], where a substantial suppression of both superconducting and magnetic properties has been found in the case of $La_{2/3}Ca_{1/3}MnO_3/YBa_2Cu_3O_{7-\delta}$ superlattices.

For most high-T_c-manganite multi-layers, the Curie temperature of the manganite layer system, T_C, well exceeds the superconducting transition, T_c. In this letter we present results of microwave measurements on $[LSMO_{(n)}/YBCO_{(8)}]_{(16)}$ and $[PCMO_{(m)}/YBCO_{(8)}]_{(16)}$ superlattices, for temperatures above and below T_c. All our samples were thin-film superlattices with typical dimensions of 5 by 10 mm^2, grown by dc magnetron sputtering at high oxygen pressure [8] and deposited onto (100)-oriented $(LaAlO_3)_{0.3}(Sr_2TaAlO_6)_{0.7}$ (LSAT) substrates [9]. Both the YBCO and $Re_{1-x}B_xMnO_3$ superlattices were *c*-axis oriented in all samples. $La_{0.67}Sr_{0.33}MnO_3$ is a ferromagnetic metal with a T_C of approx. 360 K [10], whereas $Pr_{0.8}Ca_{0.2}MnO_3$ is a ferromagnetic insulator with a T_C of approx. 150 K [11]. The nominal modulation length of the measured samples is shown in Table 1.

The microwave absorption measurements were performed in a cylindrical copper cavity having a discrete set of resonant frequencies. The cavity, with a diameter of 24 mm and a height of 6.8 mm, was connected via a cryogenic semirigid cable to the microwave vector network analyzer; all measurements were reflection-type.

TABLE I: Nominal modulation length of superlattice samples.

Sample name	unit-cells of YBaCuO	unit-cells of $La_{0.67}Sr_{0.33}MnO$	No. of repetitions
LY104	8	12	16
LY105	8	8	16
LY106	8	5	16
		unit-cells of $Pr_{0.8}Ca_{0.2}MnO$	
PrY149	8	6	16
PrY150	8	10	16
PrY151	8	14	16

The copper cavity was thermally connected to the cold-head of a cryocooler and its temperature stability was of the order ± 1 mK. We have measured the complex S_{11} reflection coefficient and calculated the unloaded Q_0-factor and resonant frequency f_0 applying the Kajfez method [12], using 80 points placed symmetrically in the vicinity of the resonant frequency.

The superlattice samples were glued in the center of the cavity end-plate and TM_{010}, TM_{011} and TM_{110} cavity-modes were applied, generating an *electric* field component perpendicular to the film surface and parallel to the *c*-axis. For the latter mode, the microwave *magnetic* field at the sample position is close to the maximum, whereas for the former two modes it is close to the minimum [13]. The electric field orientation was *orthogonal* to the one commonly used for surface resistance measurements. Such field orientation allows for the observation of the Josephson Plasma Resonance (JPR) [14], which is sensitive to the local vortex arrangement in high-T_c superconductors with an intrinsic layered structure, like the BiSrCaCuO [15] or TlBaCaCuO compounds [16].

The microwave absorption and the resonant frequency recorded for sample LY105 are presented in Fig. 1. The microwave absorption is given by ${Q_0}^{-1} - {Q_{substr}}^{-1}$, where Q_0 is the measured unloaded Q-factor of the cavity with superlattice sample and Q_{substr} is the unloaded Q of the cavity with a clean LSAT substrate of the same size *vs* temperature, which was measured separately, in order to rule out possible artifacts. The recorded curves for clean LSAT substrates are smooth, monotonic and similar for all three frequencies, the microwave absorption was always increasing as function of temperature, and is accompanied by a smooth decrease of the resonant frequency f_0 due to the thermal expansion of the copper cavity. The maximum microwave absorption in the sample always coincides with the maximum slope of the resonant frequency (proportional to the dispersive response of the sample). Data measured for sample PrY150 are shown in Fig. 2. In this case a double resonance can be clearly seen on both curves. This feature can be attributed to the superlattice inhomogeneity, *i.e.* to a slightly different thickness of some areas of the film. We have cut a smaller piece, of dimensions approx. 4 by 5 mm, out of sample PrY150. The results of this measurement are presented in Fig. 3. The two maxima become less pronounced but remain clearly visible on the frequency *vs.* temperature curve (indicated by vertical arrows).

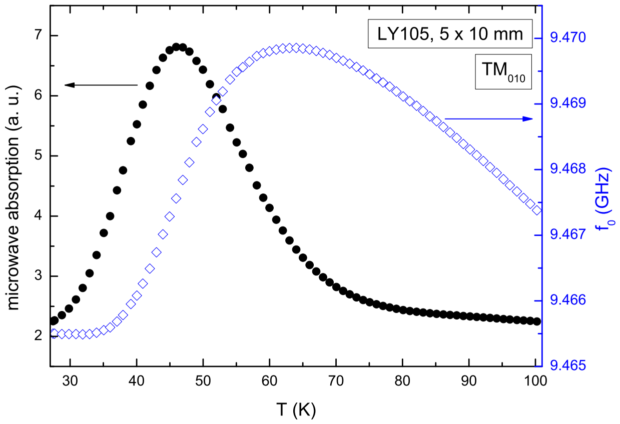

FIG. 1: Microwave absorption and resonant frequency of multi-layer film LY105.

We did not observe any such pronounced and well–defined maxima of the microwave absorption for any of the other investigated samples, nor for the measurements performed on the aforementioned samples at the higher frequencies of approx. 15 and 20 GHz, corresponding to the TM_{110} and TM_{011} modes, respectively, where a smooth decrease of the microwave absorption was observed when cooling the samples.

The observed maxima at 9.5 GHz can be explained in the context of the theoretical model developed by Takahashi *et al.* [17]. This predicts a strong frequency dependence of the high-frequency Josephson current for a S/F/S Josephson junction with a halfmetallic ferromagnetic barrier, exposed to circularly polarized microwaves. According to their model, the ac Josephson current exhibits a peak close to the frequency of the ferromagnetic resonance (FMR) and drops to zero elsewhere. The external applied magnetic field (which was zero during the course of our measurements) can be replaced by the anisotropy field H_a of the ferromagnet. Thus, according to Takahashi *et al.*, we obtain a maximum ac Josephson current at a frequency Ω_0, given by $\Omega_0 = \gamma H_a$, where γ is the gyromagnetic ratio. (An anisotropy field of approx. 3400 Oe corresponds to a frequency of 9.5 GHz). Moreover, the Josephson current does not have to increase continuously down to low temperature, it may exhibit a broad maximum between 0 K and T_c (see Fig. 3b of [17]). In order to explain our experimental results, we assume that our superlattice sample can be described by a stack of $n-1$ such S/F/S Josephson junctions, where n is the number of superconducting layers.

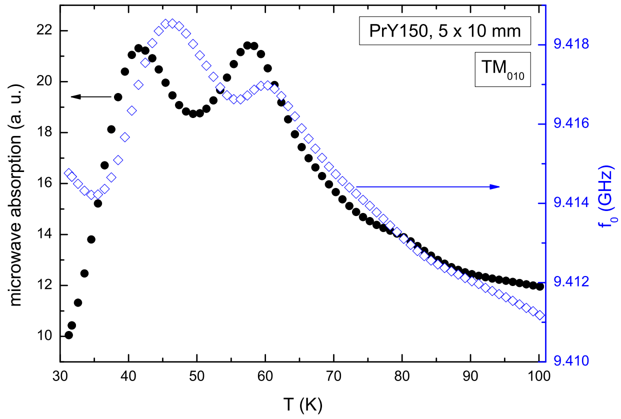

FIG. 2: Microwave losses and resonant frequency of multi-layer film PrY150.

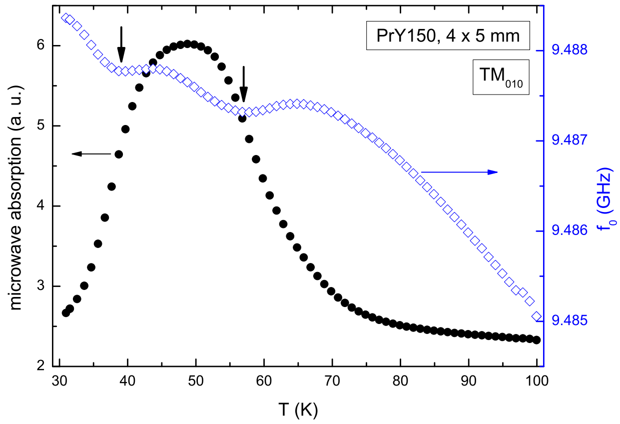

FIG. 3: Microwave losses and resonant frequency of a smaller part of multi-layer film PrY150.

For a single manganite $La_{0.7}Sr_{0.3}MnO_3$ thin film with a T_C of 330 K the anisotropy field H_a at low temperature may be as high as 10500 Oe (approx. 3900 Oe at room-temperature) [1], whereas other experimental data [18] indicate that the reduction of strain in the manganite films yields lower anisotropy fields. The measurement of the anisotropy field H_a for $[S/F]_n$ superlattices at low temperatures below T_c remains an unresolved problem due to the large magnetic hysteresis loop generated by the superconductor which masks the magnetic contribution of the ferromagnetic manganite film [9]. Therefore, only estimates of H_a can be obtained for $[S/F]_n$ superlattices, based on measurements carried out at temperatures above T_c. These estimates yield values between 5600 and 5900 Gs at 75 K for a $[LSMO_{(16u.c.)}/YBCO_{(8u.c.)}]_{(16)}$ multi-layer on $LaAlO_3$ [10]. However, our superlattices were deposited on LSAT substrates which assure a better lattice matching between the manganite and the LSAT substrate as compared to the $LaAlO_3$ substrate, which may further reduce the anisotropy field of the investigated multilayers. We are also aware that the real interfaces between the manganite and the superconductor within the superlattice are certainly more complex than assumed in the theoretical paper of Takahashi *et al.*. It was confirmed that at the YBCO/manganite interfaces very thin intermediate layers exist, i.e. 1 unit cell of non-superconducting YBCO and 3 unit cells of nonmagnetic manganite [19] which may result in additional effects not included in the theory.

We would like also to point out that the difference of the frequency behaviour observed for samples LY105 and PrY150 can not be explained within the Buravov-Shchegolev model [20] and a transition from the skin-depth penetration regime to the depolarization regime can be excluded in our case. The so called *depolarization peak* usually occurs when the sample undergoes e.g., a metal-insulator transition or a superconducting transition [21]. It manifests itself by an absorption peak *vs* T, accompanied in general by a corresponding resonant frequency minimum. However, in our case we do not have any such transitions in the temperature range of the maximum absorption observed between 40 and 57 K.

In conclusion, we have found that microwave absorption in ReMO/YBCO superlattices displays a strong frequency-dependence, in qualitative agreement with the theoretical model worked out by Takahashi *et al.* [17].

The authors are grateful to Dr. M. Jaworski for helpful remarks on cylindrical microwave resonators. We acknowledge partial support of MNiSW Grants under research project for the years 2006-2009 (MNiSW -1 P03B 122 30) and No. N202 058 32/1202.

---

* Electronic address: `Piotr.Gierlowski@ifpan.edu.pl`

[1] M. Golosovsky, P. Monod, P. K. Muduli, R. C. Budhani, L. Mechin, and P. Per, Phys. Rev. B **76**, 184414 (2007).
[2] J. Wosik, L.-M. Xie, M. Strikovski, P. Przysłupski, M. Kamel, V. V. Srinivasu, and S. A. Long, J. Appl. Phys. **91**, 5384 (2002).
[3] see e.g. M. Hein, T. Kaiser, and G. Müller, Phys. Rev. B **61**, 640 (2000) and references therein.
[4] A. Pimenov, A. Loidl, P. Przysłupski, and B. Dabrowski, Phys. Rev. Lett. **95**, 247009 (2005).
[5] V. Pena, C. Visani, J. Garcia-Barriocanal, D. Arias, Z. Sefrioui, C. Leon, J. Santamaria, and C. A. Almasan, Phys. Rev. B **73**, 104513 (2006).
[6] T. Holden, H.-U. Habermeier, G. Cristiani, A. Golnik, A. Boris, A. Pimenov, J. Humlíček, O. I. Lebedev, G. van Tendeloo, B. Keimer, and C. Bernhard, Phys. Rev. B **69**, 064505 (2004).
[7] F. Chen, B. Gorshunov, G. Cristiani, H.-U. Habermeier, M. Dressel, Solid State Commun. **131**, 295 (2004).
[8] P. Przysłupski, I. Komissarov, W. Paszkowicz, P. Dłużewski, R. Minikayev, and M. Sawicki, J. Appl. Phys. **95**, 2906 (2004).
[9] P. Przysłupski, I. Komissarov, W. Paszkowicz, P. Dłużewski, R. Minikayev, and M. Sawicki, Phys. Rev. B **69**, 134428 (2004).
[10] P. Przysłupski, A. Tsarou, P. Dłużewski, W. Paszkowicz, R. Minikayev, K. Dybko, M. Sawicki, B. Dabrowski, and C. Kimaball, Supercond. Sci. Technol. **19**, S38 (2006).
[11] Y. Tokura, Rep. Prog. Phys. **69**, 797 (2006).
[12] D. Kajfez, *Q-factor*, (Vector Fields, Oxford, MS, 1994).
[13] J. P. Kinzer and I. G. Wilson, Bell System Tech. J. **26**, 31 (1947).
[14] L. N. Bulaevskii, D. Dominguez, M. P. Maley, and A. R. Bishop, Phys. Rev. B **54**, 7521 (1996) and A. E. Koshelev, L. N. Bulaevskii, and M. P. Maley, Phys. Rev. B **62**, 14403 (2000).
[15] S. Colson, M. Konczykowski, M. B. Gaifullin, Y. Matsuda, P. Gierłowski, Ming Li, P. H. Kes, and C. J. van der Beek, Phys. Rev. Lett. **90**, 137002-1-4 (2003).
[16] V. K. Thorsmolle, R. D. Averitt, T. Shibauchi, M. F. Hundley, and A. J. Taylor, Phys. Rev. Lett. **97**, 237001 (2006).
[17] S. Takahashi, S. Hikino, M. Mori, J. Martinek, and S. Maekawa, Phys. Rev. Lett. **99**, 057003 (2007).
[18] Y. Suzuki, Appl. Phys. Lett. **71**, 142 (1997).
[19] K. Dybko, K. Werner-Malento, P. Aleshkevych, M. Wójcik, M. Sawicki, and P. Przysłupski, Phys. Rev. B **80**, 144504 (2009).
[20] L. I. Buravov and I. F. Shchegolev, Prib. Tekh. Eksp. (engl.) 528, **14** (1971).
[21] D.-N. Peligrad, B. Nebendahl, M. Mehring, A. Dulčić, M. Požek, and D. Paar, Phys. Rev. B **64**, 224504 (2001).